Effect of Condensate Flow Rate on Retention Angle on Horizontal Low-Finned Tubes

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1. Abstract

The paper reports experimental results using simulated condensation on eight horizontal integral finned tubes with different fin spacing but same root diameter. Condensation was simulated with low approaching zero vapor velocity of condensate using three liquids (water, ethylene glycol and R141b) supplied to the tube via small holes between the fins along the top of the tubes. Controlling parameters of the investigation were fin spacing of condensation tubes, flow rate of condensate and surface tension to density ratio of the condensate. The results indicate that the retention angle (measured from the top of the tube to the position where the inter-fin space is completely filled with liquid) increases with the increase in fin spacing. Also, retention angle increases as the density of the condensate increases but retention angle decreases with increase in surface tension. Interesting finding is seen as retention angle remains constant with increase in condensate flow rate, starting from very low (nearly zero) flow rate to the flow rate at which the tube gets fully flooded. The critical flow rate for eight tubes of defined fin density against three working fluids is measured. Results obtained from simulated condensation for almost zero condensate velocity are in good agreement with earlier data and theoretical model for retention angle on such tubes [1].

Keywords: *finned tubes, condensate retention, condensation, heat transfer enhancement*

2. Introduction

Low finned tubes are used extensively in condensation heat transfer applications, owing to their enhanced heat transfer capability [2]. Significant heat transfer enhancement is obtained due to increase in surface area of such condensing tube [3, 4]. Moreover, fins provide additional drainage due to surface tension induced pressure gradients, which facilitates higher heat transfer rates. However, surface tension causes condensate retention in the inter-fin space, causing decrease in heat transfer rate. During condensation of vapor on finned tube, condensate retention in inter-fin spaces due to capillary retention causes thickening of condensate film and decrease in heat transfer. The condensate retention is measured from top of the tube to the point of abrupt increase in condensate thickness, known as "retention" or "flooding" angle [1].

In order to quantify the flooding angle, Honda et al. (1983) [1] developed theoretical model for horizontal-trapezoidal fins under static conditions, given by Eq. (1)

$$\varphi_f = \left(\frac{4\sigma \cos\beta}{\rho g s d_0} - 1 \right) \qquad (1)$$

This theoretical model was also validated by several researchers independently by Owen et al. (1983) and Rudy and Webb (1985) [5, 6]. Briggs (2005) compared the experimental results with Eq. (1) using a range of fluids and geometries and experimental results under static conditions were within 15% of those obtained using Eq. (1) [7]. More recently Claire et al. (2012) obtained experimental retention angle using water, ethylene glycol and R113 [8]. Again, good agreement was obtained with Eq. (1).

Design of finned tubes involves careful estimation of design variable such as fin height, thickness and spacing. Increasing number of fins over a particular length increases surface area but causes smaller fin spacing. Whereas, condensate retention angle decreases with decreasing fin-spacing especially for fluids with higher surface tension to density ratio. Extensive experimental research has been conducted using steam, ethylene glycol and R-113 [9, 10]. Similarly, detailed theoretical heat transfer models have been developed by Bella et. al. (1993) [11] and Cavallini et al. (1994) [12]. These models predicted non-steam data within the accuracy of 25 %, whereas, steam data was not predicted accurately. Wang and Rose (2007) presented a more accurate model based on Eq. (2) [13]

$$\alpha_{sh} = \alpha_{tip} \left(\frac{t}{p} \right) \left(\frac{d_o}{d} \right) + \alpha_{root} \left(\frac{\varphi_{obs}}{\pi} \right) \left(\frac{s}{p} \right) \qquad (2)$$

Retention angle, ϕ_{obs} was based on the measured or determined from Eq. (1). The discrepancies in predicting heat transfer using theoretical models is probably due to lack of available data and mathematical models to determine retention angle at high condensation rates. More recently, data have been made available for simulated condensation on finned tube over a range of vapor velocity (0 - 24 m/s) [14]. The results indicate that retention angle is less than about π/2 at zero air velocity; it increases with increasing air velocity. On the other hand, for cases where the retention angle is greater than about π /2 at zero air velocity it decreases with increasing air velocity. In recent years, extensive experimental and theoretical work is reported on three dimensional horizontal pin-fin tubes, the effect of condensate retention on heat transfer on such tubes is also a critical problem [15-23].

In industrial condensers, vapor velocity and consequently condensation rates are higher. A complete theoretical model should account for a better estimated retention angle, rather than the one determined from Eq. (1) under static, un-inundated tube conditions. In the present paper, effect of condensate flow rate was systematically investigated using eight low fin tube geometries and three different fluids (water, ethylene glycol and R141b). For static conditions results were validated using available data and theoretical model of Honda et al. (1983) [1].

3. Equipment and procedure

Present investigation is focused on the effect of condensate flow rate on retention angle by using simulated condensation, in order to reduce data for different condensates having different physical properties and using tubes of defined geometry. Three liquids (water, ethylene glycol and R141b) were supplied to the tube having small holes between the fins along the top. The tube under test was located horizontally, as shown in fig. 1.

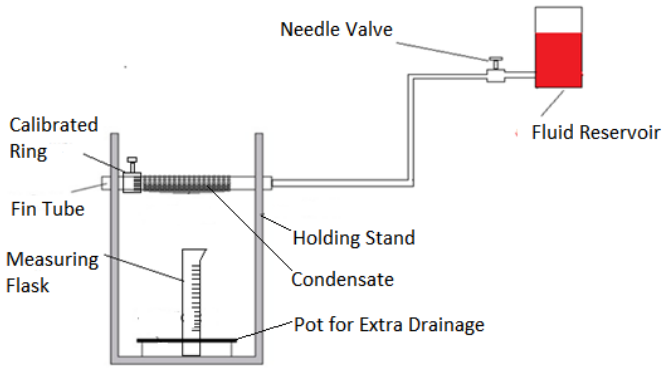


Figure 1. Schematic of apparatus

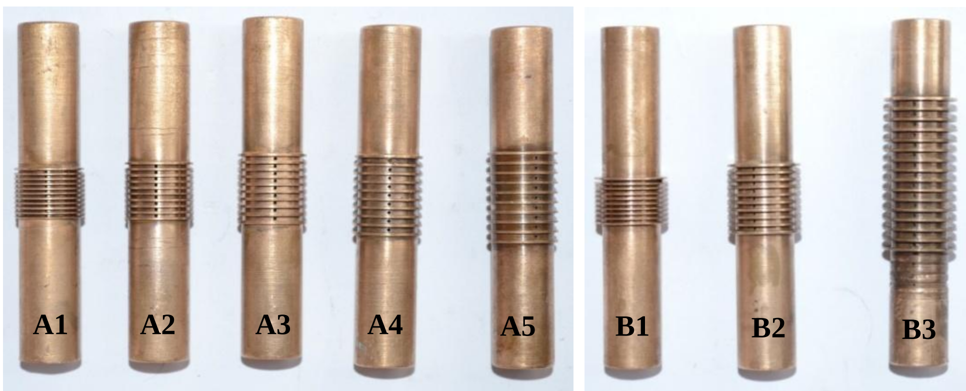


Figure 2. Finned tube for simulated condensation

Eight tubes with different fin dimensions and diameter at the fin root 12.7 mm were tested, shown in fig.2 and details summarized in tab. 1. The tubes had 0.4 mm diameter holes drilled between the rectangular section fins at the upper side of the tube. One end of the tube was connected to a fluid reservoir via a flexible tube and a needle valve to control the flow rate.

The tube diameter at the fin root was 12.7 mm in all cases. For each tube, experiments were conducted using three fluids: water, ethylene glycol and R-141b. Before the test, the tubes were thoroughly cleaned using a sodium bicarbonate solution and observed to be fully wetted by the test fluid. The flow rate was adjusted so that the fluid spilled steadily and uniformly over the tube surface.

Table 1: Dimensions of tubes used in simulated condensation experiment

Tube	s (mm)	d (mm)	t (mm)	h (mm)	d_o (mm)	Fin Density (fpm)
A1	0.50	12.7	0.5	0.8	14.3	1000
A2	0.75	12.7	0.5	0.8	14.3	800
A3	1.00	12.7	0.5	0.8	14.3	666
A4	1.25	12.7	0.5	0.8	14.3	571
A5	1.50	12.7	0.5	0.8	14.3	500
B1	0.60	12.7	0.3	1.6	15.9	1111
B2	1.00	12.7	0.5	1.6	15.9	666
B3	1.50	12.7	0.5	1.6	15.9	500

A small amount of food coloring was added to water and ethylene glycol to enhance visibility of the retention position. The fact that measurements with almost zero condensate flow rate agreed closely with Eq. (1) shows that adding small amounts of food coloring did not affect the surface tension significantly. Photographs were taken for each tube at the flow rate starting from nearly zero flow rate which was attained by spraying the condensate over the tube and measuring the retention angle, and ending at the flow rate at which the tube gets fully flooded. Measuring flask and stop watch were used to measure flow rate. Two methods were used to measure the retention angle, as given below.

3.1. Photographic method

In this method, tubes were mounted horizontally and test fluid flowed vertically downward from the tube. The tube was loaded with the fluid up to the point where flooding level on the tube becomes constant, and a photograph was taken using a digital camera. Photographs were enhanced and retention angles were then calculated by image processing. The accuracy of photographic method was within ± 0.05d.

3.2. Calibrated ring method

In this method horizontal integral-fin tubes were mounted with a calibrated ring having angles from zero to 360 degree engraved over it, as shown in fig. 3. This ring has inner diameter same as the fin root diameter with a small tolerance so that it slides over the tube. Zero error is done by adjusting the small holes aligned with the 0 degree of calibrated ring. The retention angle was then measured with the help of that ring. The accuracy by using this method was about +2 degree.

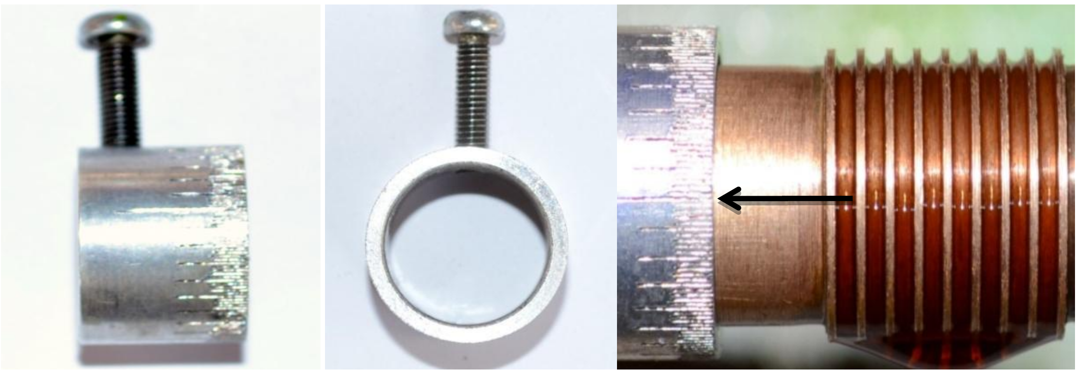


Figure 3. Calibrated ring and retention angle measurement by calibrated ring.

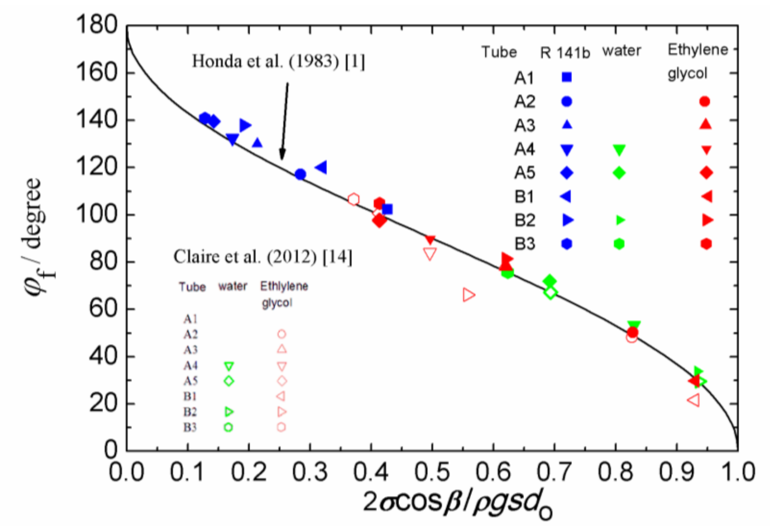


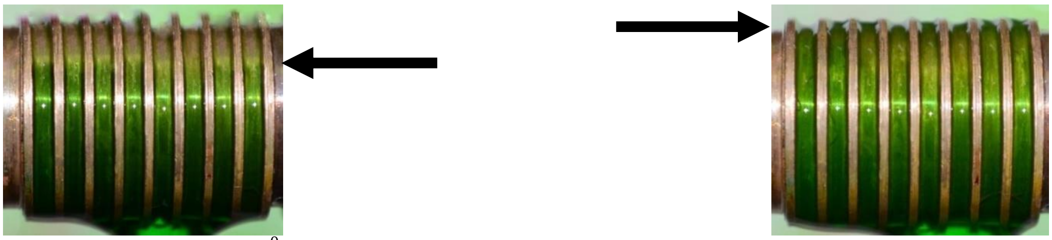
Figure 4. Comparison of present data with earlier data of Claire et al. (2012) and model of Honda et al. (1983) [14, 1]

4. Results and discussion

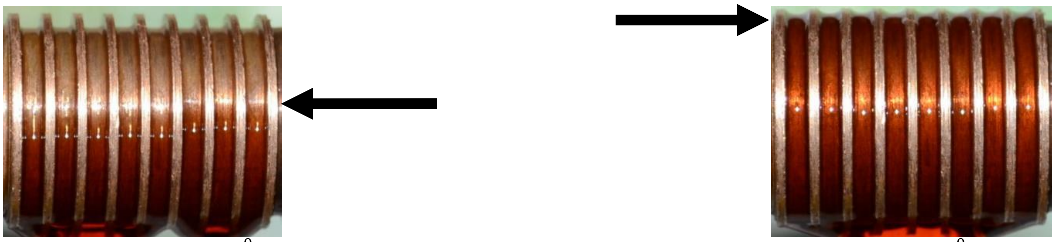
Experiments were conducted using eight different tubes with water, ethylene glycol and R141b as working fluid. Care was taken to clean the tube using sodium bicarbonate solution. The results for zero condensate flow rate were validated with available experimental data and theoretical model of Honda et al. (1983), given by Eq. (1), as shown in fig. 4. This equation is valid for a wide range of fluid properties and tube geometries and is validated by several researchers [2, 13, 14] . As could be seen in fig. 4, good agreement was obtained. Retention angles of A1, A2, A3, and B1 for water and A1 for ethylene glycol are not incorporated in the graph as they are fully flooded at nearly approaching zero condensate flow rates.

Fig. 5 shows sample photographs for tube A4 showing retention angle using water, ethylene glycol and R141b as working fluid. Retention angle was measured at approaching to zero flow rate and increasing it gradually and till the flow rate at which the tube gets fully flooded. Graphical representation of condensate retention for water, ethylene glycol and R141b are shown in fig. 6. For nearly zero condensate flow rates, tubes A1, A2, A3, B1 and tube A1 were fully flooded in case of water and ethylene glycol respectively.

Results indicate that retention angle increases by increasing the fin spacing for the same working fluid. It is interesting to note that the retention angle remains the constant until the critical flow rate was achieved.

(a) 

$\dot{m}$=0 ml/sec-mm, $\varphi_f = 56^0$ - Water $\dot{m}$=0.066 ml/sec-mm, $\varphi_f = 0^0$-Water

(b) 

$\dot{m}$=0ml/sec-mm, = 95^0 – E. Glycol $\dot{m}$=0.02 ml/sec-mm, $\varphi_f = 0^0$ – E. Glycol

(c) 

$\dot{m}$=0 ml/sec-mm, $\varphi_f = 137^0$ – R141b $\dot{m}$=0.032ml/sec-mm, $\varphi_f = 136^0$ – R141b

Figure 5. Retention angles on tube A4 for different condensate flow rates (a) water (b) ethylene glycol (c) R141b

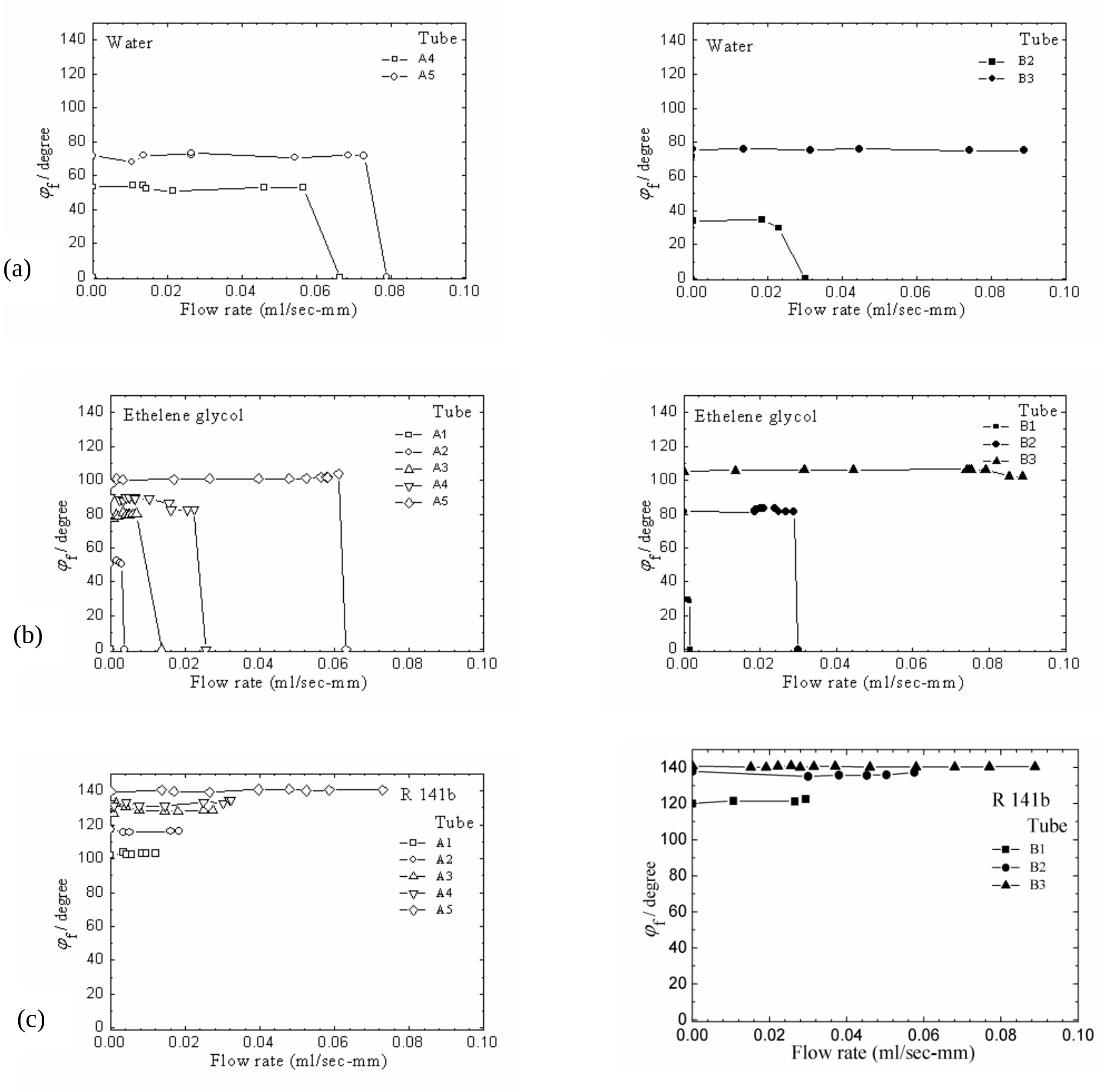


Figure 6. Retention angle versus condensate flow rate (a) water (b) ethylene glycol (c) R141b

Surface tension to density ratio for water, ethylene glycol and R141b are 72, 43 and 14 ($\mu Nm^2/kg$) respectively. It was observed that retention angle increasing with decreasing surface tension to density ratio of the condensate. As shown in fig. 5, the case of finned tube A4, condensate retention angle increased from around 80 degree to 140 degree as surface tension to density ratio is decreased from 72 to 14 ($\mu Nm^2/kg$) corresponding to water and R141b respectively.

5. Conclusions

Fin Spacing is one of the most important parameter and has been widely studied by previous researchers. For a better heat transfer surface area is needed which can be achieved by lowering the fin spacing and increasing the fin density, while maintaining the condition of tube as un-flooded. In the present paper, effect of condensate retention is noted on various fin spacing using eight different copper tubes, using three working fluids over a range of condensate flow rates.

In industrial condensers, the condensation rates can be appreciably high. Higher condensation rates lead to increased condensate flooding and consequently lower heat transfer rates are obtained. The present work extends the Honda et. al (1983), Briggs (2005) and Claire et al. (2012) and data has been provided over a range of condensate flow rates using eight different tubes and three working fluids [1, 7, 14]. The paper provides a substantial data base for future theoretical studies on condensation on low-finned tubes and shall facilitate the design of compact heat exchangers. The optimum flow rate of condensate for each fin spacing may help control the liquid loading rate in various heat transfer and air-conditioning applications, as beyond this flow rate, no significant heat transfer is obtained.

6. Nomenclature

d	fin root diameter of tube
d_o	outside diameter of tube, including fin height
g	specific force of gravity
h	fin height
s	space between adjacent fins
p	fin pitch
t	fin thickness
α	mean vapour-side heat-transfer coefficient
α_{sh}	heat-transfer coefficient due to shear effect of vapor velocity
α_{tip}	heat-transfer coefficient at fin tip
α_{root}	heat-transfer coefficient at fin root diameter
β	half angle at fin tip
σ	surface tension
ρ	density of condensate
φobs	observed “flooding” or retention angle measured from top of tube
φ_f	flooding or retention angle

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